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ABSTRACT of ONR project:
The primary result accomplished during this ONR project was the development of an ocean model of intermediate complexity that is able to simulate accurately the diurnal and annual cycles of mixed-layer thickness at the WHOI mooring site in the Arabian Sea. Modifications that allowed this success were: i) allowing the density jump at the bottom of the mixed layer to vary realistically throughout the day; and ii) including a diurnal-thermocline layer. When a biological model is coupled to this physical model, the response is improved in that blooms are weakened and broadened by the diurnal variability; however, the variability associated with active and break periods of the monsoon have a much larger effect on the blooms. The addition of salinity variability is essential for simulating mixed-layer variability in the Bay of Bengal where rainfall and river runoff are intense. In contrast, salinity effects are much smaller in the Arabian Sea where these forcings are an order of magnitude weaker.

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NOVA
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February 11, 1999

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Dear Sir,

This letter is the final report for ONR Grant No. N000149710077, entitled "A numerical investigation of mixed-layer processes in the Arabian Sea." This grant began on November 1, 1996, and ended on September 30, 1998. The project involved simulating mixed-layer variability and upper-ocean circulation throughout the Indian Ocean, with an emphasis on the Arabian Sea. There were several parts to the work. I describe our accomplishments in each part in the remainder of this letter.

Model development: The primary research task was the development of an ocean model of intermediate complexity (*i.e.*, a model considerably simpler than a state-of-the-art GCM) that was able to reproduce mixed-layer-thickness variability at diurnal through annual time scales throughout the Indian Ocean, and in particular at the WHOI mooring site in the Arabian Sea (Weller *et al.*, 1998, *Deep-Sea Res.*). The model is an improvement of the $2\frac{1}{2}$-layer, reduced-gravity system of McCreary *et al.* (1993, *Prog. Oceanogr.*; MKM). It consists of 4 active layers with thicknesses h_i $(i = 1, 4)$, overlying a quiescent, deep ocean where pressure gradients are assumed to vanish. Each of the layers represents either a specific water-mass type or dynamically important region: the surface mixed layer (layer 1), the diurnal thermocline (layer 2), the seasonal thermocline (layer 3), and the main thermocline (layer 4). The bottom panel of Figure 1 illustrates the layer structure of the upper three layers, the interface beneath layer 4 (not shown) being located at a depth of about 350 m.

Water is also allowed to move across the interfaces between layers (that is, to entrain into or detrain from them) with velocities w_i. Velocity w_1 is crucial because it determines the model's mixed-layer physics. It is specified as in the Kraus and Turner (1967, *Tellus*) model, in which entrainment and detrainment are related to the production of turbulent kinetic energy $\mathcal{P}$ by wind stirring $\mathcal{W}$ and the surface buoyancy flux $\mathcal{B}$ $(\mathcal{P} = \mathcal{W} - \mathcal{P})$ and w_1 is inversely proportional to the density jump at the bottom of the layer, $\Delta\rho$.

The improved model differs from the MKM system in two fundamental ways. First, $\Delta\rho$ is now set realistically to be the density difference between layers 1 and 2, whereas in the

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MKM model it was set to a constant value of 0.0001 gm/cm^2. This change is necessary for the model to develop a realistic diurnal cycle: Only with this change can w_1 become large enough to deepen h_1 sufficiently at night when there is surface cooling. Second, the present model also includes an extra "diurnal thermocline" layer. This layer allows the system to "remember" physical (and biological) variables when the mixed layer thins during the day. Without this layer, variables are often erroneously mixed down into the seasonal thermocline by the diurnal cycle. Realizing the necessity for, and then implementing, this layer in the model, was the most significant model-development advance made on this project.

Simulation: To simulate the mixed-layer response at the WHOI mooring site, we forced the model as follows. First, we drove the system with monthly climatological winds until the solution adjusted to an equilibrium annual cycle. Then, for the time period from April 1993 through October 1995 and over most of the model domain, the model was forced by FNMOC wind stress $\boldsymbol{\tau}$ and scalar wind w_s fields (kindly provided by John Kindle) and by monthly climatological fields of air temperature T_a, specific humidity q_a, and net solar radiation Q_r (Rao *et al.,* 1989, *J. Geophys. Res.*). Finally, from October 1994 to October 1995 and within 500 km of the WHOI mooring (15.5°N, 61.5°E), daily-mean buoy data was blended into these forcing fields in such a way that they are composed *entirely* of buoy data at the mooring site. Diurnal variability was introduced by specifying Q_r to go through a realistic diurnal cycle.

Figure 1 plots mixed-layer thickness from the buoy data h_m (top panel) and from the solution h_1 (thick curve, bottom panel). The two thicknesses are strikingly similar. Note, for example, that their maximum values are large during the two monsoons (winter and summer) and thin during the transition seasons (spring and fall), and that their diurnal cycles are large during winter and small during the summer. The most prominent difference between two thicknesses is that h_m shallows at the end of November 1994 and during August 1995 but h_1 does not, a difference likely due to the passage of eddies through the mooring area (Weller, *priv. comm.*).

In the solution, and likely the observations as well, the cause of the difference in diurnal amplitudes between the two monsoons is the size of $\mathcal{W}$. During the Northeast Monsoon, the winds and hence $\mathcal{W}$ are weak, so that $\mathcal{P}$ is dominated by $-\mathcal{B}$, which changes sign daily (from being positive during the day due to Q_r and to negative during the night due to latent heat loss); as a consequence, w_1 also changes sign daily and the diurnal cycle is large. During the Southwest Monsoon, however, $\mathcal{W}$ is large, and can become so large that $\mathcal{P}$ *never* changes sign and there is no diurnal cycle. This situation happens in h_1 during the first half of July, and apparently (almost) occurs in h_m during most of the summer.

Ecosystem model: In a previous project partly funded by ONR, we coupled a biological model to the MKM physical model to study the annual cycle of biological activity in the Arabian Sea. Results from this study were reported in McCreary *et al.* (1998, *Prog. Oceanogr.*; MKHO). A deficiency of the MKHO solution is that its spring and fall blooms are too intense

and short-lived in comparison with the observations, a limitation also shared by most other coupled systems. We hypothesized that the cause of this discrepancy was that the MKHO and other models lack a diurnally varying mixed layer as follows: In the MKHO solution, h_1 is thick enough during the winter and summer to suppress phytoplankton growth (by lowering the depth-averaged light intensity), and so the onset of blooms is delayed until the mixed layer thins at the end of each season; with diurnal variability h_1 could thin enough each day to allow phytoplankton growth, even though its daily-averaged value was too large to allow blooms to develop.

To explore this hypothesis, we obtained solutions to a coupled model consisting of the MKHO biological model and the improved physical model discussed above. These solutions confirm that diurnal variability does broaden and weaken the spring and fall blooms, but not as much as much as we had hoped. Instead, there is much more improvement when forcing by climatological winds is replaced by the actual winds at the buoy site: Apparently, variability associated with active and break periods of the monsoon (which last for a week or more) is sufficient to trigger blooms, but the short-term diurnal variability is not.

Salinity effects: Finally, Weiqing Han (graduate student) and I have added salinity to the Indian-Ocean model. Shetye (1991, *priv. comm.*) has pointed out that the mixed layer is usually shallow (or even absent) in the Bay of Bengal, in contrast to our wintertime solution which has a deep mixed layer in the northern Bay. The likely reason for this lack is the intense rainfall and river runoff in the Bay, which inhibits entrainment by lowering the density of the mixed layer. We have modified the formulation of entrainment in the model to include the effects of salinity on density, and our initial solutions corroborate this hypothesis. There are also modifications to the mixed-layer response in the Arabian Sea, but they are not as large as in the Bay because forcing by rainfall and river runoff is so much weaker there. This research is part of Weiqing's thesis research, and hopefully will be published sometime this year.

Sincerely,

Julian P. McCreary, Jr.

cc: Barbara Sterry, NSU Contracts and Grants Officer

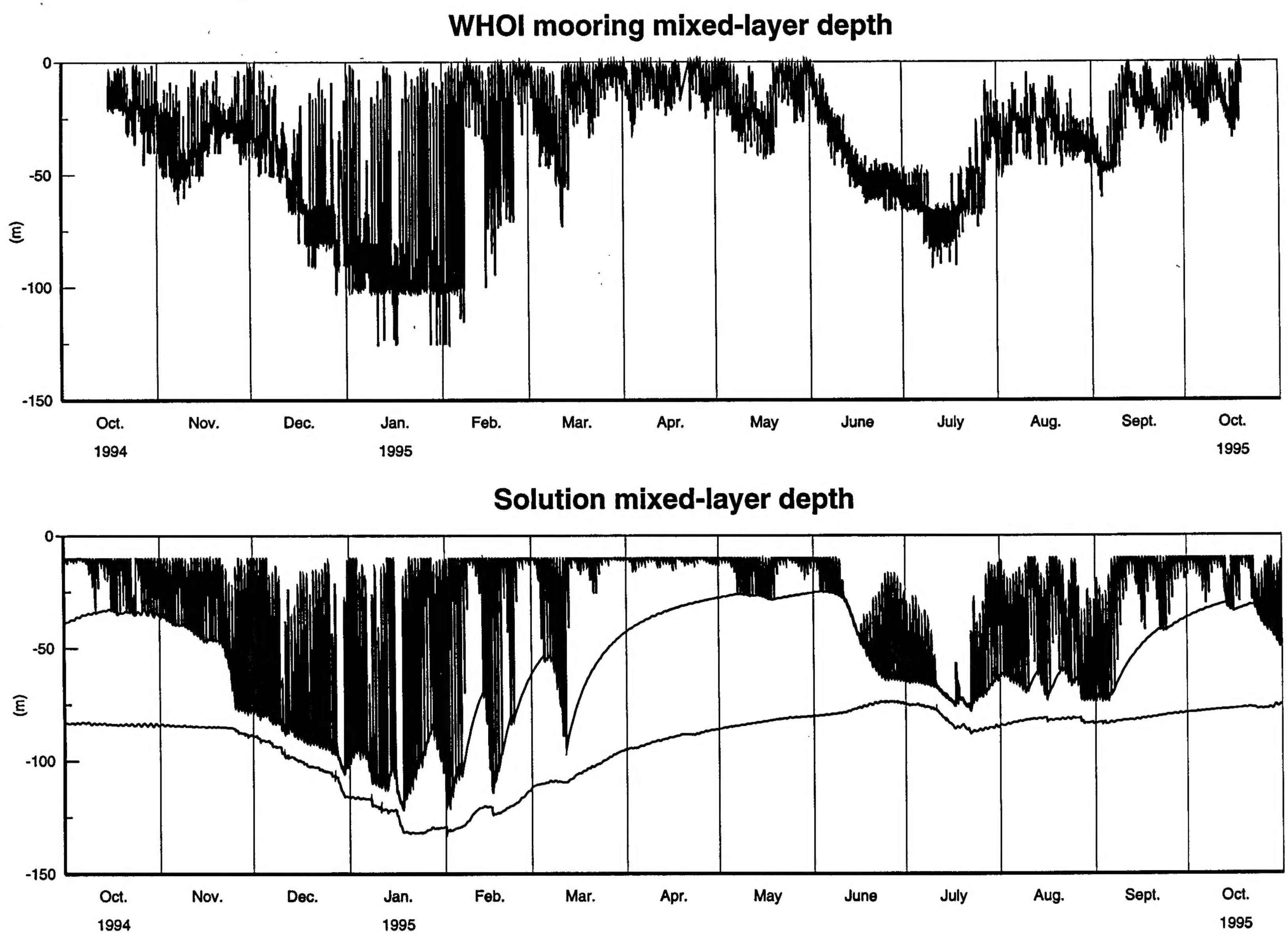

Figure 1: Time plots of mixed-layer thickness in the central Arabian Sea from the WHOI mooring h_m (top panel), as estimated by the depth at which ocean temperature is 0.1°C less than SST, and from the solution h_1 (bottom panel). The thin curves in the bottom panel are $h_1 + h_2$ and $h_1 + h_2 + h_3$. To ensure model stability, h_1 and h_3 are not allowed to become thinner than 10 m.